Direct Analysis of Spectra of Type Ic Supernovae

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ABSTRACT

Synthetic spectra generated with the parameterized supernova synthetic–spectrum code SYNOW are compared with observed photospheric–phase optical spectra of the normal Type Ic SN 1994I and the peculiar Type Ic SNe 1997ef and 1998bw. The observed spectra can be matched fairly well with synthetic spectra that are based on spherical symmetry and that include lines of just a few ions that are expected to appear on the basis of LTE calculations. Spectroscopic estimates of the mass and kinetic energy of the line–forming layers of the ejected matter give conventional values for SN 1994I but high kinetic energy ($\sim 30 \times 10^{51}$ erg) for SN 1997ef and even higher ($\sim 60 \times 10^{51}$ erg) for SN 1998bw. It is likely that even if SNe 1997ef and 1998bw were non–spherical, they also were hyper–energetic.

1. Introduction

The photospheric–phase spectrum of a Type Ic supernova lacks the strong hydrogen lines of a Type II, the strong optical He I lines of a Type Ib, and the deep red Si II absorption of a Type Ia. A Type Ic (SN Ic) is thought to be the result of the core collapse of a massive star that either has lost its helium layer or ejects helium that remains insufficiently excited to produce conspicuous optical He I lines. For a review of observations of supernova spectra, see Filippenko (1997).

Since April, 1998, interest in SNe Ic has been very high because of the extraordinary SN 1998bw, which appears to have been associated with the gamma ray burst GRB 980425 (Galama et al. 1998; Kulkarni et al. 1998). Recently we (Millard et al. 1999) have used the parameterized supernova synthetic–spectrum code SYNOW to make a "direct analysis" of spectra of SN 1994I, a well observed, normal SN Ic. In this contribution, after summarizing our work on SN 1994I, I report some preliminary results of a similar analysis of the peculiar Type Ic SN 1997ef (Deaton et al. 1998; J. Millard et al., in preparation) and then consider the related but even more peculiar SN 1998bw. The emphasis here is on establishing line identifications and making spectroscopic estimates of the mass and kinetic energy of the line–forming layers of the ejected matter.

2. SYNOW

In its simplest form the SYNOW code assumes spherical symmetry and that line formation takes place by resonant scattering outside a sharp photosphere that radiates a blackbody continuum. To a good approximation the simple explosion velocity law, $v = r/t$, holds. Consequently the velocity gradient is isotropic and homogeneous (unlike the case of a stellar wind, where even in the constant–velocity case the velocity gradient is neither isotropic nor homogeneous). From the point of view of an observer, the (nonrelativistic) surfaces of constant radial velocity are planes perpendicular to the line of sight, and an unblended line formed by resonant scattering has an emission component that peaks at the line rest wavelength in the supernova frame and an absorption component whose minimum is blueshifted by an amount that corresponds to the velocity at the photosphere (unless the line is extremely weak or rather strong).

SYNOW treats line formation in the Sobolev approximation, which is a good one for this purpose. The profile of an unblended line is determined by the adopted radial dependences of the line optical depth and the line source function. The line optical depth determines the strength of the line and is given by

$$\tau_l = \frac{\pi e^2}{m_e c}\ f\ \lambda\ t\ n_l(v) = 0.026\ f\ \lambda_\mu\ t_d\ n_l(v),$$

where f is the oscillator strength, λ_μ is the line wavelength in microns, t_d is the time since explosion in days, and $n_l(v)$ is the population of the lower level of the transition in cm^{-3}. The correction for stimulated emission, although not written out here, is taken into account.

The line source function determines the extent to which the line is in emission or absorption. In the resonant–scattering approximation line photons are conserved, except for occultation effects, and the source function of an isolated line is just the product of the intensity of the photospheric continuum and the geometrical dilution factor. The source function of a line that interacts with one or more lines of shorter wavelength is altered by photons that are scattered by those lines. The essential role of SYNOW is to treat the multiple scattering, which in observers' language is line blending.

Various fitting parameters are available for a SYNOW synthetic–spectrum calculation. T_{bb} is the temperature of the blackbody continuum radiated by the photosphere. For each ion whose lines are introduced, the optical depth at the photosphere of a reference line is a parameter, and the optical depths of the other lines of the ion are calculated for Boltzmann excitation at excitation temperature T_{exc} (which ordinarily is taken to be the same as T_{bb}). For the spectra shown here, the radial dependence of the line optical depths is a power law, $\tau \propto v^{-n}$. At each epoch, the velocity at the photosphere, v_{phot}, is a parameter, and maximum and minimum velocities also can be imposed on an ion; when the minimum velocity exceeds v_{phot} the ion is said to be detached from the photosphere. The most interesting parameters are the velocity parameters and the "density" power–law index, n.

When deciding which ions to introduce, we are guided by experience and by the LTE calculations of line optical depths by Hatano et al. (1999), who considered six compositions that might be encountered in supernovae. The composition of interest here is the one in which hydrogen and helium have been burned to a mixture of carbon and oxygen, with the heavier elements present in their solar mass fractions. In this case, ions that are predicted to have lines of significant optical depth include Ca II, Fe II, O I, Si II, C II, Mg II, O II, and Ti II.

3. The Normal Type Ic SN 1994I

In Millard et al. (1999) we compare SYNOW synthetic spectra with observed spectra of SN 1994I obtained by Filippenko et al. (1995) from 5 to 35 days after the assumed explosion date of March 30, 1994. A density power–law index of $n = 8$ is used for all epochs. Figure 1 compares a spectrum of SN 1994I obtained 16 days after explosion with a synthetic spectrum that has $v_{phot} = 10,000$ km s^{-1} and $T_{bb} = 8000$ K. Most of the observed features are well matched. Ions that certainly must be introduced to account for observed features are Ca II, O I, Na I, Fe II, and Ti II. (The Na I D–line feature is not predicted to be significant by Hatano et al. (1999), but as usual in supernova spectra the Na I feature is observed to be stronger than predicted. We are confident of the identification.) In this particular synthetic spectrum, lines of C II also are used, but detached at 16,000 km s^{-1} so that λ6580 can account for most of the observed absorption near 6200 Å. Often it is difficult to decide between detached C II λ6580 and undetached Si II λ6355, and the C II identification is not considered to be definite. In order to account for the observed absorption around 7000 Å we would have to introduce lines of O II (see below). The excessive height of the synthetic peaks in the blue part of the spectrum is not of great concern; the number of lines of singly ionized iron–peak elements rises rapidly toward short wavelengths, so SYNOW spectra often are underblanketed in the blue due to missing lines of iron–peak ions that are not introduced.

In Millard et al. (1999) we consider the identification of the observed absorption near 10,250 Å, which has been identified as He I λ10830 and taken as strong evidence that SN 1994I ejected helium (Filippenko et al. 1995). We find that it is difficult to account for even just the core of the observed 10,250 Å absorption with He I λ10830 without compromising the fit in the optical (see also Baron et al. 1999). We suggest that the observed feature may be a blend of He I λ10830 and C I λ10695, or perhaps a blend of Si I lines. This is an important issue but it will not be discussed further here, since we have no evidence for or against the presence of the feature in SNe 1997ef and 1998bw.

Another comparison of observed and synthetic spectra, but for just five days after the assumed explosion date, is shown in Figure 2. (We often consider photospheric–phase spectra in reverse chronological order, because at the earliest times line formation takes place in the highest–velocity layers and the blending is most severe.) The synthetic spectrum has $v_{phot} = 17,500$ km s^{-1} and $T_{bb} = 17,000$ K. Ions that certainly are needed are Ca II, O I, and Fe II. In this synthetic spectrum, lines of C II, Na I, Mg II, Si II, and O II (with only [O II] λ7320,7330 having a significant effect on the spectrum) also are introduced; they are considered probable but not definite.

The adopted values of v_{phot} can be used to estimate the mass and kinetic energy in the line–forming layers. For an r^{-n} density distribution, the mass (in $M_\odot$) and the kinetic energy (in foe, where 1 foe $\equiv 10^{51}$ erg) above the layer at which the electron–scattering optical depth is τ_{es} can be expressed as

$$M = 1.2 \times 10^{-4}\ v_4^2\ t_d^2\ \mu_e\ \tau_{es}\ f_M(n, v_{max}),$$

$$E = 1.2 \times 10^{-4}\ v_4^4\ t_d^2\ \mu_e\ \tau_{es}\ f_E(n, v_{max}),$$

where v_4 is v_{phot} in units of 10^4 km s^{-1}, t_d is the time since explosion in days, μ_e ($\equiv Y_e^{-1}$) is the mean molecular weight per free electron, and the integration is carried out to velocity v_{max}. The functions f_M and f_E always exceed unity.

For SN 1994I, we use $\mu_e = 14$ (a mixture of singly ionized carbon and oxygen), $\tau_{es} = 2/3$ at the bottom of the line–forming layer, and integrate the steep density power–law to infinity ($f_M(8, \infty) = 1.4$, $f_E(8, \infty) = 2.3$). Figure 3 shows v_4, M, and E plotted against time. (E should increase monotonically with time. Its non–monotonic behavior just reflects the imprecision of our determinations of v_{phot}; recall that $E \propto v_{phot}^4$.) At 35 days after explosion, the mass moving faster than 7000 km s^{-1} is estimated to be about 1.4 $M_\odot$ and it carries a kinetic energy of about 1.2 foe. These numbers are reasonable, and similar to those that have been estimated for SN 1994I on the basis of light–curve studies (Nomoto et al. 1994; Iwamoto et al. 1994; Young, Baron, & Branch 1995; Woosley, Langer, & Weaver 1995).

Such spectroscopic estimates of mass and kinetic energy also come out to be reasonable for Type Ia supernovae (Branch 1980) and for SN 1987A (Jeffery & Branch 1990).

4. From SN 1994I to SNe 1997ef and 1998bw

Figure 4 compares spectra of SN 1994I at 16 days after explosion, SN 1997ef at 20 days after its assumed explosion date of November 15, 1997, and SN 1998bw at 16 days after its explosion date of April 25, 1998. It is clear that SNe 1997ef and 1998bw are spectroscopically related to each other and also, but less closely, to SN 1994I. Therefore it seems appropriate to refer to SNe 1997ef and 1998bw as "Type Ic peculiar". The observed absorption features are much broader and bluer in SN 1997ef than in SN 1994I, and even moreso in SN 1998bw. This means that SNe 1997ef and 1998bw ejected more mass at high velocity. Figure 5 shows the effects, on the SYNOW synthetic spectrum of Figure 1 (for SN 1994I at 16 days), of raising v_{phot} from 10,000 to 30,000 km s^{-1}. Figure 6 shows the effects of dropping the density power–law index from $n = 8$ to $n = 2$. Raising v_{phot} and dropping n both cause the absorption features to become broader and bluer, and both appear to be necessary to obtain satisfactory SYNOW fits to spectra of SNe 1997ef and 1998bw. A value of $n = 2$ is used for all of the synthetic spectra shown below.

4.1. Fitting spectra of SN 1997ef

Figure 7 compares a spectrum of SN 1997ef obtained 34 days after explosion with a synthetic spectrum that has v_{phot} = 7000 km s^{-1}, T_{bb} = 7000 K, and uses only lines of Ca II, O I, Si II, and Fe II. This fit (and those to follow) could be improved by tuning the parameters, but as it stands it is good enough to indicate that we are on the right track.

Figure 8 compares a spectrum of SN 1997ef obtained 20 days after explosion with a synthetic spectrum that has $v_{phot} = 12,000$ km s^{-1}, $T_{bb} = 11,000$ K, and uses lines of Ca II, O I, Si II, Fe II, and Mg II. In the red part of the spectrum, the good fit indicates that at this epoch just a few lines of Ca II, O I, and Si II are responsible for the features. In the blue, Fe II blends dominate. The synthetic spectrum is severely underblanketed in the blue due to missing lines of other singly ionized iron–peak elements.

Figure 9 compares a spectrum of SN 1997ef obtained 10 days after explosion with a synthetic spectrum that has $v_{phot} = 22,000$ km s^{-1}, $T_{bb} = 11,000$ K, and uses the same ions as in Figure 8. This is a good example of why it can be instructive to work backward in time; this interpretation of the spectrum might seem arbitrary if the later–epoch spectra had not already been discussed.

Figure 10 is exactly like Figure 9 except that the Fe II lines have been turned off. Comparison of Figures 9 and 10 shows how strongly the Fe II lines affect the blue, while having practically no effect in the red. The same is true for the 20 and 34 day spectra discussed above.

4.2. Fitting spectra of SN 1998bw

Figure 11 compares a spectrum of SN 1998bw obtained 28 days after explosion with a synthetic spectrum that has $v_{phot} = 7000$ km s^{-1}, $T_{bb} = 6000$ K, and uses lines of Ca II, O I, Si II, Na I, Ca II, and Fe II. The situation is much like that of SN 1997ef at 34 days.

Figure 12 compares a spectrum of SN 1998bw obtained 16 days after explosion with a synthetic spectrum that has $v_{phot} = 17,000$ km s^{-1}, $T_{bb} = 8000$ K, and uses only lines of Ca II, O I, Si II, and Fe II. The situation is like that of SN 1997ef at 20 days, but here the blending is more severe due to the higher v_{phot} of SN 1998bw.

Figure 13 compares a spectrum of SN 1998bw obtained 8 days after explosion with a synthetic spectrum that has $v_{phot} = 30,000$ km s^{-1}, $T_{bb} = 8000$ K, and uses only lines of O I, Si II, Ca II, and Fe II. Again the situation is like that of SN 1997ef at 10 days but with more blending due to higher v_{phot}.

Figure 14 is like Figure 13 except that the Fe II lines have been turned off.

4.3. Masses and kinetic energies of SNe 1997ef and 1998bw

Figure 15 compares the adopted values of v_{phot} versus time. Around 30 days after explosion the v_{phot} values converge to about 7000 km s^{-1}, but at earlier times the values for SN 1997ef are higher than those for SN 1994I, and the values for SN 1998bw are higher still.

To estimate the masses and kinetic energies of SNe 1997ef and 1998bw, the integration cannot be extended to infinity because $n = 2$ has been used for the synthetic spectra. Instead the integration is carried out to $v_{max} = 2v_{phot}$ (with $f_M(2,2) = 2, f_E(2,2) = 4.7$) for the earliest epoch considered, i.e., to 44,000 km s^{-1} for SN 1997ef and to 60,000 km s^{-1} for SN 1998bw. The results are shown in Figures 16 and 17. For SNe 1997ef and 1998bw, the masses above 7000 km s^{-1} are estimated to be around 6 $M_{\odot}$. For SN 1997ef the kinetic energy above 7000 km s^{-1} comes out to be around 30 foe while that of SN 1998bw is around 60 foe. These kinetic energies are more likely to be too low than too high because most of the estimated kinetic energy comes from the earliest epochs considered, and the integrations are carried out to only $2v_{phot}$ while the synthetic spectra actually go to higher velocities. Of course, there also is more mass at velocities lower than 7000 km s^{-1}, but not much more kinetic energy.

In a preprint, Iwamoto et al. (1998) compare observed spectra of SN 1997ef with synthetic spectra calculated for a hydrodynamical model that has an ejected mass of about 4.6 $M_{\odot}$ and a kinetic energy of 1 foe. The prominent lines in their synthetic spectra are much the same as the ones that have been identified here but as they discuss, the lines in their synthetic spectra are much too narrow and not sufficiently shifted to the blue. Synthetic spectra calculated for models having more mass and kinetic energy give much better fits to the SN 1997ef spectra (P. Mazzali and K. Nomoto, personal communication). Iwamoto et al. (1999) compare observed spectra of SN 1998bw with synthetic spectra calculated for a hydrodynamical model that has an ejected mass of about 11 $M_{\odot}$ and a kinetic energy of 30 foe. Their synthetic spectra match the SN 1998bw spectra fairly well, and it appears that more mass at high velocity would lead to even better fits.

5. Conclusion

The spectroscopic mass and kinetic–energy estimates presented here for SNe 1997ef and 1998bw are preliminary and approximate. Nevertherless, it seems clear that at least in the spherical approximation the kinetic energy of both events was much higher than the canonical one foe, as was reported by Deaton et al. (1998) for SN 1997ef and as in the models of Iwamoto et al. (1999) and Woosley, Eastman, & Schmidt (1999) for SN 1998bw.

Polarization spectra are much more sensitive than flux spectra to asymmetry. Core–collapse supernovae generally show detectable polarization, which indicates that they are significantly asymmetric (Wang et al. 1996). Höflich, Wheeler, & Wang (1999) calculate light curves of moderately asymmetric explosions and suggest that SN 1998bw was distinguished principally by having been viewed close to the symmetry axis, rather than by having a very high kinetic energy. It is true that to the extent that the ejecta of SNe 1997ef and 1998bw are “beamed”, the kinetic energy estimates presented here might be too high. However, because the spectra of SNe 1997ef and 1998bw can be matched fairly well in a straightforward way with the spherical symmetry assumption, and the corresponding kinetic–energy estimates are so very high, and the Lorentz factor of the ejecta is not high enough to *be* a factor in the energy estimates, it is likely that even if SNe 1997ef and 1998bw were non–spherical, they also were hyper–energetic.

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Fig. 1.— A spectrum of SN 1994I obtained 16 days after explosion is compared with a synthetic spectrum (dashed line). The flux is per unit frequency.

Fig. 2.— A spectrum of SN 1994I obtained 5 days after explosion is compared with a synthetic spectrum. The flux is per unit frequency.

Fig. 3.— Velocity at the photosphere (in units of 10,000 km s^{-1}), and mass (in $M_{\odot}$) and kinetic energy (in foe) above the photosphere, are plotted against time for SN 1994I.

Fig. 4.— A spectrum of SN 1994I (Filippenko et al. 1995) is compared with spectra of SN 1997ef (P. Garnavich et al., in preparation) and SN 1998bw (F. Patat et al., in preparation). In this and subsequent figures the flux is per unit wavelength.

Fig. 5.— The dashed line is the synthetic spectrum of Figure 1. The solid line shows the effects of raising v_{phot} from 10,000 to 30,000 km s^{-1}.

Fig. 6.— The dashed line is the synthetic spectrum of Figure 1. The solid line shows the effects of dropping n from 8 to 2.

Fig. 7.— A spectrum of SN 1997ef (Y. Qiu et al., in preparation) obtained 34 days after explosion is compared with a synthetic spectrum.

Fig. 8.— A spectrum of SN 1997ef (P. Garnavich et al., in preparation) obtained 20 days after explosion is compared with a synthetic spectrum.

Fig. 9.— A spectrum of SN 1997ef (P. Garnavich et al., in preparation) obtained 10 days after explosion is compared with a synthetic spectrum.

Fig. 10.— The synthetic spectrum is like that of Figure 9 except that the Fe II lines have been turned off.

Fig. 11.— A spectrum of SN 1998bw (F. Patat et al., in preparation) obtained 28 days after explosion is compared with a synthetic spectrum.

Fig. 12.— A spectrum of SN 1998bw (F. Patat et al., in preparation) obtained 16 days after explosion is compared with a synthetic spectrum.

Fig. 13.— A spectrum of SN 1998bw (F. Patat et al., in preparation) obtained 8 days after explosion is compared with a synthetic spectrum.

Fig. 14.— The synthetic spectrum is like that of Figure 13 except that the Fe II lines have been turned off.

Fig. 15.— Velocity at the photosphere (in units of 10,000 km s^{-1}) is plotted against time.

Fig. 16.— Spectroscopic estimates of mass (in $M_{\odot}$) above the photosphere are plotted against time.

Fig. 17.— Spectroscopic estimates of kinetic energy (in foe) above the photosphere are plotted against time.